ENGLISH

TRANSLATION OF

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APPLICATION AS FILED

DESCRIPTION

SURFACE ACOUSTIC WAVE DEVICE

Technical Field

The present invention relates to surface acoustic wave (SAW) devices used for resonators or band-pass filters and a method for manufacturing the same. More specifically, the present invention relates to a SAW device having a structure in which an insulating layer covers an interdigital transducer (IDT) electrode.

Background Art

In duplexers (DPX) or radio frequency (RF) filters used in a mobile communication system, a wideband characteristic and a favorable temperature characteristic are required to be satisfied at the same time. SAW devices that have conventionally been used for DPXs or RF filters use a piezoelectric substrate made of 36° to 50°-rotated Y-cut X-propagating $LiTaO_3$. This piezoelectric substrate has a temperature coefficient of frequency of about -40 to -30 ppm/°C. As a method for improving the temperature characteristic, a method for forming a SiO_2 film having a positive temperature coefficient of frequency to cover an IDT electrode on a piezoelectric substrate has been known. Fig. 30 shows an example of a method for manufacturing this type of SAW device.

As shown in Fig. 30(a), a resist pattern 52 is formed on a piezoelectric substrate 51 except a region where an IDT electrode is to be formed. Then, as shown in Fig. 30(b), an electrode film 53 to serve as an IDT electrode is formed over an entire surface. Then, the resist pattern 52 and the metal film on the resist pattern 52 are removed by using a resist removing agent. In this way, an IDT electrode 53A is formed, as shown in Fig. 30(c). Then, as shown in Fig. 30(d), a SiO_2 film 54 is formed to cover the IDT electrode 53A.

The following Patent Document 1 discloses a method for manufacturing a SAW device including an insulating or semiconducting

protective film to cover an IDT electrode of the SAW device, the method having a purpose other than improving the above-described temperature coefficient of frequency. Fig. 31 is a schematic cross-sectional view showing the SAW device described in this known art. In the SAW device 61, an IDT electrode 63 made of Al or an alloy mainly containing Al lies on a piezoelectric substrate 62. An insulating or semiconducting inter-electrode-finger film 64 lies in a region except the region where the IDT electrode 63 lies. Furthermore, an insulating or semiconducting protective film 65 lies to cover the IDT electrode 63 and the inter-electrode-finger film 64. In the SAW device 61 described in this known art, the inter-electrode-finger film 64 and the protective film 65 are made of an insulating material such as SiO_2 or a semiconducting material such as silicon. According to this known art, forming the inter-electrode-finger film 63 suppresses degradation of a characteristic caused by inter-electrode-finger discharge due to a pyroelectirc property of the piezoelectric substrate 61.

On the other hand, the following Patent Document 2 discloses a one-port SAW resonator. This one-port SAW resonator is manufactured by forming an electrode made of metal such as aluminum or gold on a piezoelectric substrate made of quartz or lithium niobate, forming a SiO_2 film thereon, and then by smoothing the SiO_2 film. According to this Patent Document, a favorable resonance characteristic can be obtained by smoothing.

Patent Document 1: Japanese Unexamined Patent Application Publication No. 11-186866

Patent Document 2: Japanese Unexamined Patent Application Publication No. 61-136312

Disclosure of Invention

As shown in Fig. 30, in the known method for manufacturing a SAW

device of forming a SiO_2 film in order to improve a temperature coefficient of frequency, the height of the SiO_2 film 54 differs at a portion where the IDT electrode 53A exists and at a portion where the IDT electrode 53A does not exist. Such an uneven surface of the SiO_2 film 54 disadvantageously increases insertion loss. This unevenness becomes more significant as the IDT electrode becomes thicker. Therefore, the film thickness of the IDT electrode cannot be increased.

In the SAW device described in Patent Document 1, the inter-electrode-finger film 64 is formed between electrode fingers of the IDT electrode 63 and then the protective film 65 is formed thereon. In this method, the surface of the protective film 65 can be smoothed.

However, in the structure described in Patent Document 1, the IDT electrode 63 is made of Al or an alloy mainly containing Al. The inter-electrode-finger film 64 contacts the IDT electrode 63, but a sufficient reflection coefficient cannot be obtained in the IDT electrode 63. Accordingly, ripple is easy to occur in a resonance characteristic, for example.

In the manufacturing method described in Patent Document 1, a resist formed on the inter-electrode-finger film 64 must be removed by using a resist removing agent before forming the protective film 65. At this time, however, the IDT electrode 63 may be corroded by the resist removing agent. For this reason, a metal susceptible to corrosion cannot be used as a material of the IDT electrode. In other words, the type of metallic material of the IDT electrode is limited.

On the other hand, in the one-port SAW resonator described in Patent Document 2, a specific embodiment includes only an example in which an electrode made of Al is formed on a quartz substrate, although it is described that quartz or lithium niobate is used for the piezoelectric substrate and that the electrode is made of aluminum or gold. That is, this Patent Document does not refer to a SAW device using another substrate material or another metallic material.

An object of the present invention is based on the above-described circumstances of the known arts and is to provide a SAW device in which an insulating layer lies between electrode fingers of an IDT electrode and on the IDT electrode and a method for manufacturing the same. More specifically, an object of the present invention is to provide a SAW device having a favorable resonance and filter characteristics, in which the reflection coefficient of an IDT electrode is sufficiently high and degradation of characteristic due to ripple in the resonance characteristic can be suppressed, and a method for manufacturing the same.

Another object of the present invention is to provide a SAW device not only having a favorable characteristic with a sufficiently high reflection coefficient of an IDT electrode but also having a high degree of freedom in selecting a metallic material of the IDT electrode and being capable of suppressing an adverse effect of corrosion of the IDT electrode, and a method for manufacturing the same.

Another object of the present invention is to provide a SAW device not only having a favorable characteristic with a sufficiently high reflection coefficient of an IDT electrode and being capable of suppressing degradation of characteristic due to corrosion of the IDT electrode but also having a favorable temperature coefficient of frequency, and a method for manufacturing the same.

According to a first invention, there is provided a surface acoustic wave device including a piezoelectric substrate made of $LiNbO_3$ having an electromechanical coupling coefficient whose square (k^2) is 0.025 or more; at least one electrode that is made of a metal whose density is higher than that of Al or an alloy mainly containing the metal or that is composed of laminated films made of a metal whose density is higher than that of Al or an alloy mainly containing the metal and another metal, the electrode lying on the piezoelectric

substrate; a first insulating layer lying in a region other than a region where the at least one electrode lies, the thickness of the first insulating layer being almost equal to that of the electrode; and a second insulating layer covering the electrode and the first insulating layer. The density of the electrode is more than 1.5 times higher than that of the first insulating layer.

According to a second invention, there is provided a surface acoustic wave device including a piezoelectric substrate made of $LiNbO_3$; at least one electrode lying on the piezoelectric substrate; a protective metal film made of a metal or alloy that is more corrosion-resistant than a metal or alloy contained in the electrode, the protective metal film lying on the electrode; a first insulating layer lying in a region other than a region where the at least one electrode lies, the thickness of the first insulating layer being almost equal to the total thickness of the electrode and the protective metal film; and a second insulating layer covering the protective metal film and the first insulating layer.

According to a specific aspect of the second invention, an average density of an entire laminated structure including the electrode and the protective metal film is more than 1.5 times higher than the density of the first insulating layer.

According to a specific aspect of the first and second inventions, the first and second insulating layers are made of SiO_2.

According to another specific aspect of the first and second inventions, reflection of surface acoustic waves is used in the surface acoustic wave device.

According to another specific aspect of the first and second inventions, the height of a convex portion on a surface of the second insulating layer is 0.03λ or less when the wavelength of a surface acoustic wave is λ.

According to another specific aspect of the surface acoustic wave

device of the first and second inventions, the height of a convex portion on the second insulating layer is 1/2 or less of the thickness of the electrode.

More preferably, the height of the convex portion is 1/3 or less of the thickness of the electrode.

According to another specific aspect of the surface acoustic wave device of the first and second inventions, the electrode mainly contains a metal heavier than Al.

According to another specific aspect of the surface acoustic wave device according to the first and second inventions, the electrode mainly contains a metal selected from a group consisting of Au, Pt, Cu, Ta, W, Ag, Ni, Mo, NiCr, Cr, and Ti.

According to another specific aspect of the surface acoustic wave device of the present invention, the electrode is made of Au or Pt and the thickness thereof is in the range of 0.0017λ to 0.06λ when the wavelength of a surface acoustic wave is λ.

According to another specific aspect of the surface acoustic wave device of the present invention, the electrode mainly contains a metal selected from a group consisting of Au, Ag, Ni, Mo, Zn, Cu, Pt, Ta, W, Cr, and Ti, and the thickness of the electrode is in the range shown in the following Table 1 when the wavelength of a surface acoustic wave is λ.

[Table 1]

Au	0.0017λ ~ 0.06λ
Pt	0.0017λ ~ 0.06λ
Ag	0.0035λ ~ 0.10λ
Ta	0.0025λ ~ 0.064λ
W	0.0035λ ~ 0.06λ
Cu	0.0058λ ~ 0.11λ
Ni	0.012λ ~ 0.12λ
Cr	0.012λ ~ 0.12λ
Ti	0.012λ ~ 0.12λ
Mo	0.012λ ~ 0.12λ
Zn	0.012λ ~ 0.12λ

According to another specific aspect of the surface acoustic wave

device of the present invention, the thickness of the second insulating layer is in the range of 0.15λ to 0.4λ when the wavelength of a surface acoustic wave is λ.

Preferably, the thickness of the first insulating layer is in the range of 0.2λ to 0.3λ when the wavelength of a surface acoustic wave is λ.

According to another specific aspect of the surface acoustic wave device according to the present invention, Euler angles of the piezoelectric substrate made of $LiNbO_3$ are in the ranges shown in the following Table 2.

[Table 2]

Euler angles
(0±5, 62~167, 0±10)
(0±5, 87~158, 20±10)
(0±5, 112~165, 80±10)
(0±5, 107~167, 100±10)
(10±5, 110~162, 80±10)
(10±5, 69~108, 100±10)
(10±5, 72~140, 160±10)
(20±5, 99~121, 160±10)
(30±5, 67~113, 0±10)
(30±5, 27~125, 140±10)
(30±5, 67~103, 160±10)

According to another specific aspect of the surface acoustic wave device according to the present invention, Euler angles of the piezoelectric substrate made of $LiNbO_3$ are in the ranges shown in the following Table 3.

[Table 3]

$k_R^2 \leq 0.01$
(0±5, 80～160, 0±10)
(0±5, 100～142, 0±10)
(0±5, 112～165, 80±10)
(0±5, 107～167, 100±10)
(10±5, 123～158, 80±10)
(10±5, 74～90, 100±10)
(10±5, 87～128, 160±10)
(20±5, 99～119, 160±10)
(30±5, 82～98, 0±10)
(30±5, 28～53, 140±10)
(30±5, 70～103, 160±10)

According to another specific aspect of the surface acoustic wave device according to the present invention, Euler angles of the piezoelectric substrate made of $LiNbO_3$ are in the ranges shown in the following Table 4.

[Table 4]

$k_R^2 \leq 0.049$
(0±5, 88～117, 0±10)
(0±5, 115～124, 0±10)
(0±5, 115～135, 80±10)
(0±5, 109～157, 100±10)
(10±5, 130～146, 80±10)
(10±5, 80～87, 100±10)
(10±5, 98～118, 160±10)
(20±5, 110～118, 160±10)
(30±5, 86～94, 0±10)
(30±5, 33～47, 140±10)
(30±5, 77～103, 160±10)

According to another specific aspect of the surface acoustic wave device according to the present invention, Euler angles of the piezoelectric substrate made of $LiNbO_3$ are in the ranges shown in the following Table 5.

[Table 5]

Euler angles
(0±5, 38±10, 0)
(0±5, 89±10, 77～102±5)
(0±5, 130±10, 79±5)
(10±5, 110±10, 50～80±5)
(10±5, 110±10, 106±5)
(20±5, 100±10, 35～72±5)
(20±5, 100±10, 100～110±5)
(30±5, 89±10, 40～80±5)
(30±5, 100±10, 40～117±5)

According to another specific aspect of the surface acoustic wave device according to the present invention, Euler angles of the piezoelectric substrate made of $LiNbO_3$ are in the ranges shown in the following Table 6.

[Table 6]

Euler angles
(0±5, 38±10, 0)
(0±5, 89±10, 80～100±5)
(10±5, 110±10, 50～80±5)
(20±5, 100±10, 42～70±5)
(30±5, 89±10, 42～76±5)
(30±5, 100±10, 42～72±5)

The surface acoustic wave device according to the first invention includes a first insulating layer lying in a region other than a region where at least one electrode lies, the thickness of the first insulating layer being almost equal to that of the electrode; and a second insulating layer covering the electrode and the first insulating layer. In this structure, the electrode is made of a metal having a higher density than that of the first insulating layer or an alloy mainly containing the metal, so that the electrode has a sufficient reflection coefficient. Accordingly, a SAW device capable of suppressing degradation of characteristics due to undesirable ripple and having a favorable temperature coefficient of frequency can be provided.

In addition, the thickness of the IDT electrode is almost equal to that of the first insulting layer, and the second insulating layer is laminated to cover the IDT and the first insulating layer. With this

configuration, the outer surface of the second insulating layer can be smoothed, so that degradation of characteristics due to unevenness of the surface of the second insulating layer can be suppressed.

In the first invention, the piezoelectric substrate is made of $LiNbO_3$ having an electromechanical coupling coefficient of 0.025 or more. Thus, the bandwidth can be widened.

In the surface acoustic wave device according to the second invention, the first insulating layer lies in a region other than a region where the electrode lies on the piezoelectric substrate made of $LiNbO_3$, the thickness of the first insulating layer being almost equal to that of the electrode, the protective metal film made of a metal or alloy that is more corrosion-resistant than a metal or alloy contained in the electrode lies on the electrode, and the second insulating layer covers the protective metal film and the first insulating layer. Since the electrode is covered by the protective metal film and the first insulating layer, corrosion of the electrode due to a resist removing agent can be prevented when a resist is removed by photolithography. Therefore, the electrode can be made of a metal or alloy that is easy to be corroded by a resist removing agent or the like but that has a sufficiently higher density than that of Al, for example, Cu. Accordingly, degradation of characteristics of the SAW device can be effectively suppressed.

In the second invention, when an average density of an entire laminated structure including the electrode and the protective metal film is more than 1.5 times higher than the density of the first insulating layer, the reflection coefficient of the electrode can be effectively increased.

In the first and second inventions, when the first and second insulating layers are made of SiO_2, a SAW device having an improved temperature coefficient of frequency TCF can be provided according to the present invention.

In the present invention, when the height of the convex portion on the surface of the second insulating layer is 0.03λ or less, occurrence of insertion loss can be suppressed.

When the height of the convex portion on the second insulating layer is 1/2 or less of the thickness of the electrode, insertion loss of the SAW device can be effectively suppressed. When the height of the convex portion is 1/3 or less of the thickness of the electrode, the insertion loss can be suppressed more effectively.

Brief Description of the Drawings

Fig. 1(a) to (g) are schematic partially-cutout cross-sectional views illustrating a method for manufacturing a SAW device according to an embodiment of the present invention.

Fig. 2 is a schematic plan view of a one-port SAW resonator obtained in an embodiment of the present invention.

Fig. 3 shows a relationship between a thickness H/λ of a SiO_2 film and a temperature coefficient TCF when the SiO_2 film lies on a 13°, 30°, or 70°-rotated Y-cut X-propagating $LiNbO_3$ substrate.

Fig. 4 shows a relationship between a normalized thickness H/λ of a SiO_2 film and an electromechanical coupling coefficient k^2 in a structure where an interdigital electrode and the SiO_2 film lie on a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate.

Fig. 5 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 6 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 7 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 8 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 9 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 10 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 11 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 12 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 13 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 14 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 15 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 16 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 17 shows a relationship between θ of Euler angles (φ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 18 shows a relationship between θ of Euler angles (φ, θ, ψ)

of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 19 shows a relationship between θ of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 20 shows a relationship between θ of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 21 shows a relationship between θ of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 22 shows a relationship between θ of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 23 shows a relationship between a thickness of an electrode and an electromechanical coupling coefficient k^2 in electrodes made of different metals lying on a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate.

Fig. 24 shows a relationship between a thickness of an electrode and an attenuation constant α in electrodes made of different metals lying on a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate.

Fig. 25 shows a relationship between a height of a convex portion on a surface of a SiO_2 film and insertion loss.

Fig. 26 shows a relationship between a ratio of a height of a convex portion on a surface of a SiO_2 film to a thickness of an interdigital electrode and insertion loss.

Fig. 27(a) and (b) are schematic plan views illustrating a one-port resonator and a two-port resonator as examples of a SAW device to which the present invention is applied.

Fig. 28 is a schematic plan view illustrating a ladder filter as a SAW device to which the present invention is applied.

Fig. 29 is a schematic plan view illustrating a lattice filter as a SAW device to which the present invention is applied.

Fig. 30(a) to (d) are schematic cross-sectional views showing an example of a method for manufacturing a known SAW device.

Fig. 31 is a schematic front cross-sectional view illustrating an example of a known SAW device.

Fig. 32 shows a relationship between the thickness of an electrode and a reflection coefficient when the thickness of a SiO_2 film is 0.3λ in a structure including the SiO_2 film having a smooth surface, the electrode, and a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate.

Fig. 33(a) to (e) show changes in impedance characteristic in accordance with change in ratio of an average density of an IDT electrode and a protective metal film to the density of a first insulating layer.

Fig. 34 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film having a thickness of 0.2λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to an embodiment of the present invention.

Fig. 35 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film having a thickness of 0.25λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to the embodiment of the present invention.

Fig. 36 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film having a thickness of 0.3λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to the embodiment of the present invention.

Fig. 37 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film

having a thickness of 0.35λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to the embodiment of the present invention.

Fig. 38 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film having a thickness of 0.4λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to the embodiment of the present invention.

Fig. 39 shows a relationship between the thickness of an electrode and a reflection coefficient in a SAW device including a SiO_2 film having a thickness of 0.5λ and a smooth upper surface placed on an electrode made of different metals placed on a $LiNbO_3$ substrate according to the embodiment of the present invention.

Fig. 40 shows a relationship between the thickness of an electrode and a reflection coefficient in a known SAW device including a SiO_2 film covering an IDT electrode and having an uneven surface, in which a $LiNbO_3$ substrate has Euler angles of (0°, 37.86°, 0°) and the thickness and material of the electrode is variously changed.

Fig. 41 shows a relationship between ψ in a $LiNbO_3$ substrate having Euler angles of (0°, 89°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 42 shows a relationship between ψ in a $LiNbO_3$ substrate having Euler angles of (30°, 89°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 43 shows a relationship between ψ in a $LiNbO_3$ substrate having Euler angles of (20°, 100°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 44 shows a relationship between ψ in a $LiNbO_3$ substrate having Euler angles of (30°, 100°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 45 shows a relationship between ψ in a $LiNbO_3$ substrate

having Euler angles of (10°, 110°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Fig. 46 shows a relationship between ψ in a $LiNbO_3$ substrate having Euler angles of (0°, 130°, ψ) and electromechanical coupling coefficients of a Rayleigh wave and a LSAW.

Reference Numerals

1 $LiNbO_3$ substrate

2 first insulating layer

3 resist pattern

4 metal film

4A IDT electrode

5 Ti film as protective metal film

6 second insulating layer

11 SAW resonator

12 and 13 reflector

21 SAW device

22 $LiNbO_3$ substrate

23a and 23b IDT

25 SiO_2 film

Best Mode for Carrying Out the Invention

Hereinafter, a specific embodiment of the present invention is described with reference to the drawings.

A method for manufacturing a surface acoustic wave (SAW) device according to a first embodiment of the present invention is described with reference to Figs. 1 and 2.

First, as shown in Fig. 1(a), a $LiNbO_3$ substrate 1 is prepared as a piezoelectric substrate.

A first insulating layer 2 is formed on an entire surface of the $LiNbO_3$ substrate 1. In this embodiment, the first insulating layer 2

is made of a SiO_2 film.

The first insulating layer 2 is formed by an appropriate method, such as printing, evaporation, or sputtering. The thickness of the first insulating layer 2 is equal to that of an interdigital (IDT) electrode, which is formed later.

Then, as shown in Fig. 1(b), a resist pattern 3 is formed by using photolithography. The resist pattern 3 is formed so that a resist is placed in a region except the region where the IDT electrode is to be formed.

Then, the first insulating layer 2, except a portion under the resist 3, is removed by reactive ion etching (RIE) or the like of applying ion beams, as indicated by arrows in Fig. 1(c).

If a SiO_2 film is etched by a reactive ion etching (RIE) device using a fluorine gas, a residue may be left by a polymerization reaction. In that case, the residue of the RIE can be treated with BHF (buffered hydrofluoric acid).

After that, a Cu film and a Ti film are formed such that the total thickness thereof is equal to that of the first insulating layer 2. As shown in Fig. 1(d), a Cu film 4 is formed in a region where the first insulating layer 2 has been removed, that is, in a region where an IDT is to be formed. At the same time, the Cu film 4 is formed on the resist pattern 3. Then, a Ti film 5 serving as a protective metal film to cover the entire surface is formed. As shown in Fig. 1(e), the Ti film 5 is formed on the upper surface of an IDT electrode 4A and on the Cu film 4 on the resist pattern 3. Accordingly, the IDT electrode 4A is covered by the first insulating layer 2 on its side surfaces and by the Ti film 5 on it upper surface. In this manner, the IDT electrode 4A and the protective metal film are formed, such that the total thickness of the IDT electrode 4A and the Ti film 5 serving as a protective metal film is the same as the thickness of the first insulating layer 2.

After that, the resist pattern 3 is removed by using a resist removing agent. Accordingly, the structure shown in Fig. 1(f) can be obtained. That is, the IDT electrode 4A lies in a region where the first insulating layer 2 has been removed, and the upper surface of the IDT electrode 4A is covered by the Ti film 5.

Then, as shown in Fig. 1(g), a SiO_2 film as a second insulating layer 6 is formed over the entire surface.

Accordingly, a one-port SAW resonator 11 shown in Fig. 2 is obtained.

Fig. 1(a) to (g) show only a part where the IDT electrode 4A is formed. However, as shown in Fig. 2, the SAW resonator 11 includes reflectors 12 and 13, which are placed on both sides of the IDT electrode 4A in a SAW propagating direction. The reflectors 12 and 13 are formed through the same process as that for the IDT electrode 4A.

In the above-described embodiment, the one-port SAW resonator 11 is used, and thus one IDT electrode 4A is provided on the $LiNbO_3$ substrate 1. However, a plurality of IDT electrodes may be provided according to an application of the SAW device. Further, the reflectors may be formed through the same process as that for the IDT as described above. Alternatively, the reflectors may not be provided.

The density of the IDT electrode 4A is more than 1.5 times higher than that of the first insulating layer 2, so that the IDT electrode 4A has a sufficient reflection coefficient.

SAW resonators were manufactured in the same method as that in the above-described embodiment while variously changing the density of a metal contained in the IDT electrode 4. The impedance characteristics of the respective SAW resonators obtained accordingly are shown in Fig. 33(a) to (e). Fig. 33(a) to (e) show results obtained when the ratio ρ_1/ρ_2 of an average density ρ_1 of a laminated structure of the IDT electrode and the protective metal film to a density ρ_2 of the first insulating layer is 2.5, 2.0, 1.5, 1.2, and 1.0, respectively.

As is clear from Fig. 33(a) to (e), the above-mentioned ripple A is shifted outside the band in Fig. 33(a) to (c). Particularly, the ripple A is significantly suppressed in Fig. 33(a).

As can be understood from the results shown in Fig. 33, when the density of the laminated structure including the IDT electrode and the protective metal film is more than 1.5 times higher than that of the first insulating layer, the ripple A can be shifted outside the band between a resonance frequency and an antiresonance frequency, and thus a favorable characteristic can be obtained. More preferably, the ripple can be minimized when the density ratio is 2.5:1 or more.

In Fig. 33(a) to (e), the above-mentioned average density is used according to the above-described embodiment because the Ti film lies on the IDT electrode 4A. In the present invention, however, the protective metal film need not always be provided on the IDT electrode 4A. In that case, the thickness of the IDT electrode 4A should be the same as that of the first insulating layer, and the density of the IDT electrode should be more than 1.5 times (more preferably, more than 2.5 times) higher than that of the first insulating layer. It has been verified that the same advantages as those described above can be obtained with this structure.

Therefore, in the SAW resonator including the IDT electrode covered by the SiO_2 film, if the density of the IDT electrode or the average density of the laminated structure including the IDT electrode and the protective metal film is higher than the density of the first insulating layer that is placed on side surfaces of the IDT electrode, the reflection coefficient of the IDT electrode can be increased and thus degradation in characteristic emerging between a resonance point and an antiresonance point can be suppressed.

As a metal or an alloy having a higher density than that of Al, Ag, Au, or an alloy mainly containing Ag or Au can be used as well as Cu.

Preferably, if the protective metal film is laminated on the IDT

electrode as in the above-described embodiment, corrosion of the IDT electrode 4A can be prevented when the resist pattern 3 is removed because the side surfaces of the IDT electrode 4A are covered by the first insulating layer 2 and the upper surface thereof is covered by the protective metal film 6, as is clear from the manufacturing method shown in Fig. 1(a) to (g). Accordingly, a SAW resonator having a more favorable characteristic can be provided.

Alternatively, the first and second insulating layers may be formed by using an insulating material having a temperature characteristic improving effect other than SiO_2, such as SiO_xN_y. The first and second insulating layers may be made of either different insulating materials or the same material.

In the above-described embodiment, the $LiNbO_3$ substrate 1 serving as a piezoelectric substrate should preferably be a $LiNbO_3$ substrate having an electromechanical coupling coefficient k of a SAW whose square is 0.025 or more. Accordingly, a SAW device of a wide bandwidth can be provided.

The inventors of the present application examined a relationship between Euler angles and an electromechanical coupling coefficient by variously changing Euler angles of a $LiNbO_3$ substrate.

The temperature coefficient of frequency (TCF) of $LiNbO_3$ is negative: -80 to -110 ppm/°C, which is not so favorable. For improvement, a method for improving a TCF in a SAW device by forming a SiO_2 film having a positive TCF on a $LiNbO_3$ substrate has been known.

As shown in Fig. 3, if a SiO_2 film is formed on a 13°-rotated Y-cut X-propagating (Euler angles of (0°, 103°, 0°)) $LiNbO_3$ substrate, an optimum thickness of the SiO_2 film is 0.27λ when the wavelength is λ. That is, the TCF is 0 (zero) when the thickness of the SiO_2 film is 0.27λ. The optimum thickness of the SiO_2 film varies if the azimuth angle of the $LiNbO_3$ substrate changes. However, as is clear from Fig. 1, a temperature coefficient TCF of almost 0 (zero) can be obtained

when the thickness of the SiO_2 film is in the range of 0.18λ to 0.34λ to the wavelength.

On the other hand, Fig. 4 shows a relationship between a normalized thickness H/λ of a SiO_2 film and an electromechanical coupling coefficient k^2 in a structure where an IDT electrode and a SiO_2 film lie on a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate. Fig. 4 shows results obtained in respective IDT electrodes of a 0.005λ to 0.01λ thickness made of various metallic materials.

As is clear from Fig. 4, the electromechanical coupling coefficient k^2 is lower as the thickness H/λ of the SiO_2 film is larger. Thus, the SiO_2 film should be as thin as possible.

As described above, and as is clear from Figs. 3 and 4, the thickness of the SiO_2 film should desirably be in the range of 0.2λ to 0.35λ, when both the temperature coefficient of frequency TCF and the electromechanical coupling coefficient k^2 are taken into consideration.

Under the condition where the thickness of the SiO_2 film is 0.3λ, a relationship between θ of Euler angles and an electromechanical coupling coefficient of a Rayleigh wave was examined in $LiNbO_3$ substrates of different Euler angles. The results are shown in Figs. 5 to 22.

It is generally known that a leaky surface acoustic wave (LSAW) is hardly generated when θ of Euler angles (0, θ, 0) is in the range of 20° to 40°. When a thin SiO_2 film lies on the upper surface of an IDT electrode or the like, a LSAW portion of a low electromechanical coupling coefficient ranges around 20° to 40° of θ of Euler angles (0, θ, 0), as indicated with the dotted line shown in Fig. 5.

In general, an electromechanical coupling coefficient k^2 required in a RF filter or a duplexer is 0.025 or more. In addition, if a LSAW is used, the spurious of a Rayleigh wave needs to be small. That is, when the electromechanical coupling coefficient of a Rayleigh wave is k_R^2 and when the electromechanical coupling coefficient of a LSAW is

k_{LSAW}^2, $(k_{LSAW}^2/4) \geq k_R^2$ should be satisfied.

Table 7 shows the ranges of Euler angles to satisfy such a range. Since $LiNbO_3$ is a crystal of trigonal system, Euler angles have the following relationship:

$(\phi, \theta, \psi) = (60+\phi, -\theta, \psi) = (60-\phi, -\theta, 180-\psi)$

$= (\phi, 180+\theta, 180-\psi) = (\phi, \theta, 180+\psi)$.

Thus, for example, Euler angles (10, 30, 10) are equivalent to Euler angles (70, -30, 10), (50, -30, 170), (10, 210, 170), and (10, 30, 190).

[Table 7]

Euler angles	LSAW		Rayleigh	
	k	k^2	k	k^2
(0±5, 62～167, 0±10)	0.22 ～ 0.43	0.0484 ～ 0.1849	0.02 ～ 0.17	0.0004 ～ 0.0289
(0±5, 87～158, 20±10)	0.24 ～ 0.32	0.0576 ～0.1024	0.07 ～ 0.16	0.0049 ～ 0.0256
(0±5, 112～165, 80±10)	0.16 ～ 0.22	0.0256 ～ 0.0484	0.01 ～ 0.10	0.0001 ～ 0.01
(0±5, 107～167, 100±10)	0.16 ～ 0.21	0.0256 ～ 0.0441	0.01 ～ 0.10	0.0001 ～ 0.01
(10±5, 110～162, 80±10)	0.17 ～ 0.39	0.0289 ～ 0.1521	0.05 ～ 0.17	0.0025 ～ 0.0289
(10±5, 69～108, 100±10)	0.27 ～ 0.37	0.0729 ～ 0.1369	0.07 ～ 0.18	0.0049 ～ 0.0324
(10±5, 72～140, 160±10)	0.24 ～ 0.32	0.0576 ～ 0.1024	0.06 ～ 0.15	0.0036 ～ 0.0225
(20±5, 99～121, 160±10)	0.16 ～ 0.20	0.0256 ～ 0.04	0.03 ～ 0.11	0.0009 ～ 0.0121
(30±5, 67～113, 0±10)	0.32 ～ 0.35	0.1024 ～ 0.1225	0.06 ～ 0.17	0.0036 ～ 0.0289
(30±5, 27～125, 140±10)	0.21 ～ 0.41	0.0441 ～ 0.1681	0.05 ～ 0.17	0.0025 ～ 0.0289
(30±5, 67～103, 160±10)	0.16 ～ 0.30	0.0256 ～ 0.09	0.03 ～ 0.10	0.0009 ～ 0.01

Preferably, the Euler angles should be in the ranges shown in Table 8. In that case, the electromechanical coupling coefficient k_R^2 of a Rayleigh wave is 0.01 or less.

[Table 8]

$k_R^2 \leq 0.01$
(0±5, 80～160, 0±10)
(0±5, 100～142, 0±10)
(0±5, 112～165, 80±10)
(0±5, 107～167, 100±10)
(10±5, 123～158, 80±10)
(10±5, 74～90, 100±10)
(10±5, 87～128, 160±10)
(20±5, 99～119, 160±10)
(30±5, 82～98, 0±10)
(30±5, 28～53, 140±10)
(30±5, 70～103, 160±10)

More preferably, the Euler angles should be in the ranges shown in Table 9. In that case, k_R^2 is 0.0049 or less.

[Table 9]

$k_R^2 \leq 0.049$
(0±5, 88~117, 0±10)
(0±5, 115~124, 0±10)
(0±5, 115~135, 80±10)
(0±5, 109~157, 100±10)
(10±5, 130~146, 80±10)
(10±5, 80~87, 100±10)
(10±5, 98~118, 160±10)
(20±5, 110~118, 160±10)
(30±5, 86~94, 0±10)
(30±5, 33~47, 140±10)
(30±5, 77~103, 160±10)

Fig. 23 shows electromechanical coupling coefficients k^2 in electrodes of various metallic materials lying on a 13°-rotated Y-cut X-propagating $LiNbO_3$ substrate. As is clear from Fig. 23, the electromechanical coupling coefficient k^2 changes in accordance with change in thickness of the electrode. It has been verified that the thickness of the electrode to obtain k^2 1.25 times higher than k^2 when the electrode is not formed is in the range of 0.0017 to 0.03 to the wave length, if the electrode is made of Au. Although not shown in the figure, the range of thickness is the same in an electrode made of Pt. The range is 0.0035 to 0.05 in Ag, 0.0025 to 0.032 in Ta, 0.0035 to 0.03 in W, 0.0058 to 0.055 in Cu, 0.125 to 0.08 in Ni, 0.033 to 0.12 in Al, and 0.012 to 0.12 in Cr, Ti, Mo, or Zn.

The upper limit of the above-described range of the thickness of an electrode is limited by the accuracy of forming an interdigital electrode. That is, it is difficult to form an interdigital electrode having a larger thickness than the above-described thickness with high accuracy.

The optimum thickness of an electrode differs depending on the Euler angles of a $LiNbO_3$ substrate. However, the maximum of the optimum thickness is about twice of the minimum at most.

Since the upper limit of the thickness of an electrode is 0.12λ in Al, the optimum thickness of the electrode is 0.0017λ to 0.06λ in Au, 0.0017λ to 0.06λ in Pt, 0.0035λ to 0.10λ in Ag, 0.0025λ to 0.064λ in Ta,

0.0035λ to 0.06λ in W, 0.0058λ to 0.11λ in Cu, 0.012λ to 0.12λ in Ni, and 0.033λ to 0.12λ in Al.

Fig. 24 shows change in propagation constant relative to the thickness of an electrode in SAW devices including electrodes of different materials with the above-described optimum thickness. As is clear from Fig. 24, the propagation loss is almost 0 (zero) in these thicknesses.

When the first and second insulating layers are made of SiO_2, in other words, when a SiO_2 film is formed to cover an interdigital electrode, as shown in Figs. 1 and 2, a convex portion is generated on the upper surface of the SiO_2 film due to the shape of the interdigital electrode. If the convex portion is large, that is, if the convex on the surface of the second insulating layer 6 is high, the characteristic of the SAW device degrades. Fig. 25 shows change in insertion loss according to change in height of the convex portion on the surface of the SiO_2 film. As is clear from Fig. 25, the insertion loss can be suppressed if the height of the convex portion is 0.03λ or less, which is desirable.

The height of the convex portion on the surface of the SiO_2 film is a distance from the bottom to the top of the convex portion.

Fig. 26 shows change in insertion loss when the ratio between the height of the convex portion on the surface of the SiO_2 film and the thickness of the interdigital electrode is changed. In the result shown in Fig. 26, white circles indicate the case where the normalized film thickness H/λ of the IDT is 0.06λ, black triangles indicate the case where the thickness is 0.03λ, and crosses indicate the case where the thickness is 0.08λ.

As is clear from Fig. 26, the height of the convex portion on the surface of the SiO_2 film should be half or less of the thickness of the interdigital electrode and the height should be 0.04λ or less. More preferably, the height of the convex portion should be 1/3 or less of

the thickness of the interdigital electrode and the height should be 0.03λ or less. More preferably, the surface of the SiO_2 film hardly has unevenness.

In a typical SAW device, an adequate stop band is not generated if the reflection coefficient is low. Therefore, a SAW device having a low reflection coefficient does not operate as a resonator. When a SAW device is used as a SAW resonator, the reflection coefficient of the SAW device needs to be 0.03 or more. Thus, the thickness of the electrode must be set so that a reflection coefficient of 0.03 or more can be obtained by considering a relationship between the reflection coefficient and the thickness of the electrode. Figs. 34 to 39 show a relationship between the reflection coefficient in a structure where the surface of the SiO_2 film is smoothed and the thickness of respective electrodes made of Au, Ag, Ta, Cu, W, and Al. Herein, a 127.86°-rotated Y-cut X-propagating $LiNbO_3$ substrate is used as a substrate. The Euler angles of this substrate are (0°, 37.86°, 0°).

As is clear from Figs. 34 to 39, even if the thickness of the SiO_2 film changes in the range of 0.2λ to 0.5λ, a reflection coefficient of 0.03 or more can be obtained when Au, Ag, Ta, Cu, or W (except Al) is used as a material of the electrode.

Incidentally, the range of the vicinity of the above-described Euler angles (0°, 37.86°, 0°) is the range of Euler angles in which the electromechanical coupling coefficient of a Rayleigh wave is high and the electromechanical coupling coefficient of a LSAW is low. In the range of the vicinity of these Euler angles, the reflection coefficient is almost 0 (zero). For this reason, substrates having those Euler angles have conventionally been used only in transversal filters, in which the reflection coefficient should be low. That is, this type of substrate cannot be used in devices requiring reflection of fingers as shown in Figs. 27 to 29. Furthermore, in a conventional structure having an uneven surface of a SiO_2 film, the reflection

coefficient obtained is almost the same as that when Al is used, even if a heavy metal such as Cu or Ag is used for an IDT electrode. Fig. 40 shows a relationship between a reflection coefficient and the thickness of an electrode in a conventional structure with an uneven surface of a SiO_2 film.

Fig. 40 shows change in reflection coefficient according to change in thickness of an electrode in a conventional structure where an electrode made of different metallic materials is formed on the above-described $LiNbO_3$ substrate having Euler angles of (0°, 37.86°, 0°) and a SiO_2 film having a normalized thickness of 0.4λ covers the electrode. As is clear from Fig. 40, when a $LiNbO_3$ substrate having the above-described Euler angles is used and when the electrode is made of a heavy metal such as Cu, the reflection coefficient obtained is as low as that when Al is used regardless of the thickness of the electrode.

A high electromechanical coupling coefficient of a Rayleigh wave and a low electromechanical coupling coefficient of a LSAW can be obtained in a plurality ranges of Euler angles other than the above-described range. The following Tables 10 and 11 show those ranges of Euler angles. Also, Figs. 41 to 46 show the ranges of Euler angles.

More specifically, Figs. 41 to 46 show a relationship between ψ in the cases of using $LiNbO_3$ substrates having Euler angles of (0°, 89°, ψ), (30°, 89°, ψ), (20°, 100°, ψ), (30°, 100°, ψ), (10°, 110°, ψ), and (0°, 130°, ψ), respectively, and electromechanical coupling coefficients of a Rayleigh wave and a LSAW. As is clear from Figs. 41 to 46, when $LiNbO_3$ substrates of various Euler angles are used, the electromechanical coupling coefficient of a Rayleigh wave is high and the electromechanical coupling coefficient of a LSAW is low in a plurality of ranges of Euler angles.

Table 10 shows a plurality of ranges of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate to satisfy $K_{RAY}^2 \geq 0.05$ and $K_{LSAW}^2 \leq 0.02$. Table 11 shows a plurality of ranges of Euler angles (ϕ, θ, ψ) of a $LiNbO_3$ substrate

to satisfy $K_{RAY}^2 \geq 0.05$ and $K_{LSAW}^2 \leq 0.01$.

The same characteristics as those shown in Figs. 34 to 39 can be obtained in the ranges of Euler angles shown in Tables 10 and 11. In the ranges of Euler angles shown in Tables of this description, ±5 or ±10 is tolerance of an angle calculated by considering a processing accuracy of Euler angles when the devices are mass-produced and a difference in specific gravity of a material of an electrode having a small specific gravity, such as Cu, and a material of an electrode having a very great specific gravity, such as Au.

[Table 10]

φ	θ	ψ	k		k^2	
			RAY	LSAW	RAY	LSAW
0±5	38±10	0	0.29	0.10	0.0841	0.009
0±5	89±10	77~102±5	0.22~0.31	0.06~0.14	0.050~0.096	0.004~0.020
0±5	130±10	79±5	0.27	0.13	0.073	0.017
10±5	110±10	50~80±5	0.22~0.23	0.06~0.08	0.050~0.053	0.004~0.006
10±5	110±10	106±5	0.22	0.11	0.048	0.012
20±5	100±10	35~72±5	0.22~0.24	0.04~0.14	0.050~0.058	0.002~0.020
20±5	100±10	100~110±5	0.22~0.26	0.11~0.14	0.050~0.068	0.012~0.020
30±5	89±10	40~80±5	0.24~0.28	0.04~0.14	0.056~0.078	0.002~0.020
30±5	100±10	40~117±5	0.22~0.32	0.04~0.14	0.050~0.102	0.002~0.020

[Table 11]

φ	θ	ψ	k		k^2	
			RAY	LSAW	RAY	LSAW
0±5	38±10	0	0.29	0.10	0.084	0.009
0±5	89±10	80~100±5	0.23~0.25	0.06~0.10	0.053~0.063	0.004~0.010
10±5	110±10	50~80±5	0.22~0.23	0.06~0.08	0.050~0.053	0.004~0.006
20±5	100±10	42~70±5	0.22~0.23	0.04~0.10	0.050~0.053	0.002~0.010
30±5	89±10	42~76±5	0.24~0.28	0.04~0.10	0.058~0.078	0.002~0.010
30±5	100±10	42~72±5	0.22~0.24	0.04~0.10	0.050~0.058	0.002~0.010

Fig. 32 shows a relationship between a reflection coefficient of each electrode finger of an Al electrode, a W electrode, and a Cu electrode, respectively, and the thickness of the electrode. A SiO_2 film exists between electrode fingers and on the electrode fingers.

The thickness of the SiO_2 film on the substrate is 0.3λ and the surface of the SiO_2 film is even. The substrate is made of 13°-rotated Y-cut X-propagating $LiNbO_3$. As is clear from the figure, Al electrode fingers have a low reflection coefficient, and the reflection coefficient does not become high even if the film thickness increases. In contrast, electrode fingers made of heavy W or Cu have a higher reflection coefficient than that of Al. Further, the reflection

coefficient becomes higher as the film thickness is larger. As described above, an IDT composed of electrode fingers of higher density than that of Al has a high reflection coefficient, and thus is suitable for a resonator, a resonator filter, and a ladder filter.

The present invention can be applied to various SAW devices. Examples of those SAW devices are shown in Figs. 27(a) and (b) to 29. Fig. 27(a) and (b) are schematic plan views showing electrode structures of a one-port SAW resonator 47 and a two-port SAW resonator 48, respectively. A two-port SAW resonator filter may be configured by using the same electrode structure as that of the two-port SAW resonator 48 shown in Fig. 27(b).

Figs. 28 and 29 are schematic plan views showing electrode structures of a ladder filter and a lattice filter, respectively. By forming the electrode structure of the ladder filter 49a shown in Fig. 28 or the lattice filter 49b shown in Fig. 29 on a piezoelectric substrate, a ladder filter or a lattice filter can be configured according to the present invention.

The present invention can be applied to various SAW devices, in addition to the SAW devices having the electrode structures shown in Figs. 27 to 29.